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EVALUATION AND SELECTION OF TECHNOLOGY CONCEPTS FOR A HYPERSONIC HIGH SPEED STANDOFF MISSILE

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Abstract

This paper describes the application of a method for technology concept selection to the design of a hypersonic high-speed standoff missile capable of achieving pin-point strike of long-range targets with very short dwell times, such as mobile missile launchers. The primary strengths of this method are its ability to systematically enumerate and organize a wide variety of design alternatives in a simple and elegant manner, and its ability to facilitate concept selection for multi-attribute problems. The high-speed standoff missile is used as a model for application of this technique due to the multi-attribute nature of the problem and the stringent nature of the requirements. These requirements include a 1,500 lb launch weight, 500 nmi range, less than 10 minute time to target, and a unit cost of less than $300,000. The first step in this process was to assemble a set of configuration and technology options for consideration. From these, a set of eight concepts were synthesized, evaluated, and down-selected to two alternatives: an advanced solid rocket concept, and a ramjet concept. These two designs were evaluated in detail for cost, performance, lethality, and effectiveness. The results were then used in conjunction with the TOPSIS multi-attribute evaluation technique to make a final selection.

Introduction

One need only review recent and current world events to realize that today's political climate is in some ways more unstable and uncertain than it has been in the past, particularly with the end of the cold war and the disintegration of the Soviet Union. The cold war was a struggle against a monolithic adversary whose boundaries and capabilities were reasonably well defined. No longer does the United States face the unified force of the old Soviet Union and its Eastern Bloc allies. The new adversaries are more numerous and elusive because they lie scattered among several smaller, independent nations and even factions within nations. In addition, the proliferation of mobile Weapons of Mass Destruction and other offensive weapons amongst numerous smaller countries is making it increasingly difficult to protect friendly assets against attack from theater-range mobile weapons.

This basic difficulty is further compounded by present Western military doctrine, which calls for a long-term aerial campaign in response to these threats, and generally downplays the use of ground forces in most situations. Since there are no ground forces controlling the terrain, the adversary is free to hide assets in camouflaged revetments until they are ready to be used. If it is a mobile asset, it is a simple matter to drive the weapon to a suitable launch site, set up, launch, and depart the area before allied forces have sufficient time to respond. This is especially the case when there is a vast amount of territory that must be patrolled in order to be "in the right place, at the right time." The recent engagements in Iraq (Operations Desert Storm and Desert Fox) and Kosovo (Operation Allied Force) punctuate this point.

As a consequence of this doctrine, there is currently insufficient capability to respond to targets that are highly mobile or otherwise difficult to locate. For example, surface-to-air missile (SAM) launchers and mobile theatre ballistic missiles typically have dwell times of under 10 minutes.[1] That is, these time-critical targets (TCT) may appear suddenly, or move location rapidly. The subsonic flight speeds of the current arsenal limit the timeliness of aerial responses to TCTs. As a result, today's response capability is becoming increasingly insufficient to meet the demands of tomorrow's battlefield.

This situation is prompting military planners to develop a credible military capability to respond to this threat. One approach to solve this problem is to use a High-Speed Standoff Missile (HSSM).[1] Such a weapon, capable of hypersonic speeds, would provide a force structure with the rapid reaction capability needed to accurately eliminate the TCT threat. Furthermore, with sufficient range, allied aircraft could launch this missile safely beyond the threat range of SAMs. In addition, if such a weapon were equipped with a modern multi-purpose warhead, it would greatly increase the utility and flexibility of allied response capability by allowing the weapon to be employed against a variety of targets.

This weapon alone will not meet the needs of the rapid response capability, and must instead be designed as part of a larger system architecture. This architecture must include a synergistic, real-time information and targeting environment within which the HSSM would

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operate. Thus, the concepts developed and discussed in this paper are based on a postulated 2010 capability for an advanced command, control, communication, computers, intelligence, surveillance, reconnaissance (C4ISR) network.[1] The C4ISR architecture is assumed to combine ground stations, satellite sensors relays, and unmanned air vehicle sensors to provide the launch aircraft with a sensor-to-shooter connectivity time of under 2 minutes. In addition, the C4ISR environment is assumed to offer targeting information accurate to within three meters (sufficient for an advanced GPS/INS guidance system aboard the HSSM to achieve high target accuracy, on the order of three meters circular error probable.)

Finally, *a successful HSSM program must perform with minimum possible cost.* As a result, the design concepts described in this paper place a great deal of emphasis on simplicity of design and avoidance of exotic materials and processes. It has been estimated that in order for an HSSM system to be truly practical, a reduction of more than 50% over current missile costs is needed. A sufficiently low unit cost would allow the use of HSSM in place of much more costly cruise missiles such as the conventional air-launched cruise missile (CALCM), which has a unit price of approximately $1 million.[1,2]

The design of a missile airframe capable of meeting these requirements presents several challenges. First, the stringent nature of the HSSM design requirements implies that any successful HSSM design must capitalize on a considerable number of new technologies. Fortunately, there is an abundance of promising technologies that have been proposed for use on a HSSM concept, particularly with regards to propulsion technologies. Consequently, there is an almost bewildering array of potential design solutions, certainly more than can be evaluated within the resources of any reasonable research and development effort. Therefore, the design of an HSSM missile presents a challenge with regards to how to best go about systematically enumerating and evaluating the multitudinous technology concepts such that a handful of the most promising concepts are identified for further evaluation.

Second, the HSSM is inherently a multi-objective problem wherein the merit of the design is measured by a multitude of metrics including lethality, performance, system effectiveness, etc. Therefore, any evaluation method must be capable of treating multi-criterion problems in a consistent and comprehensive way. This has historically been a stumbling block in concept evaluation due to the trend towards promulgating more design figures of merit (FoMs) with each successive generation of missile technology. Fortunately, a great deal of work is currently taking place in the field of multi-criterion decision-making methods. The missile concept selection problem stands to benefit from the application of these new methods.

The objective of this paper is to describe a technology concept selection method having unique features that facilitate systematic selection and evaluation of missile technology concepts subject to multiple criteria. This method is demonstrated for the design of an HSSM missile from initial conceptual exploration to preliminary design down-select. The design requirements are discussed in detail, and a matrix of suitable HSSM technology concepts is developed. From this initial pool of technologies, a set of eight configurations is selected for conceptual-level design development. These are then down-selected to two designs, one solid rocket-powered, and the other powered by a ramjet. Finally, these two design alternatives are evaluated for performance, cost, and lethality with the aid of multi-attribute decision-making techniques.

Approach - TIES Method

One of the major tasks in the conceptual design process is evaluation of numerous alternative concepts on a qualitative basis, before selecting a subset of baseline designs for further development. This process of alternatives synthesis and evaluation presents a considerable challenge because most of the applicable concepts involve new or untried technology for which there is little or no experience base upon which to draw for guidance in choosing the most promising design morphology. The number of possible configuration/technology combinations is usually astronomical, and as modern systems increase in complexity, the number of possible design options increases exponentially. Consequently, there is a need for methods that can assist the designer in organizing and synthesizing various alternatives to pare down the design possibilities to a tractable number that can be evaluated at a reasonable depth of analysis.

The approach used to solve this problem was to adapt methods originating in the field of decision theory for use in the aerospace systems design process. These techniques have been developed over the course of several years into a comprehensive systems design method known as Technology Impact Evaluation and Selection (TIES) Method. *TIES is in fact a purpose-built design method developed at the Georgia Tech Aerospace Systems Design Laboratory (ASDL) specifically to aid the designer in selection of technology alternatives.* Thus, its application herein is a natural extension of its original purpose, and it was used to great effect for exploring HSSM technology and configuration options. In addition, the systematic approach allows one to focus in on a few promising configurations in very short order. Although TIES is a general method, only a subset of those elements germane to the analysis conducted herein are discussed in detail. A comprehensive description of the TIES method is given in references 3 and 4.

The basic design method used for this study is depicted in the form of a flowchart shown in Figure 1. The first step is definition of the problem in terms of specific objectives and constraints. Based on this, one can develop a *morphological matrix*, which is a matrix that explicitly lists all of the major design and configuration alternatives in a simple format. The major design attributes are listed in the left column, and the possibilities for each attribute are enumerated in a row to the right of the attribute column. Once this matrix is created, one can easily generate alternative design concepts by simply selecting an option from each row, with each complete set of options defining a single configuration. This is best done through a series of free-form brainstorming sessions involving a small team of experienced designers.

Once a satisfactory set of design alternatives has been developed, they are next placed in a matrix of criteria versus concepts, known as a *Pugh matrix*. The Pugh matrix is nothing more than a systematic way of showing the alternative concepts side-by-side in a simple format. Therefore, *the Pugh matrix is a tool for summarizing and comparing the attributes of alternative configurations against each other* and against the RFP requirements. Its primary purpose in this study is to assist in the qualitative down-select from a broad pool of alternatives to a "short list" of design concepts to be studied using detailed analytical methods.

Next, the alternatives remaining on the "short list" must be evaluated via modeling and simulation to determine system attributes and performance. The result of this process is a set of disparate performance figures of merit that must somehow be combined into a single figure of merit to arrive at a winning design configuration. What is needed is some systematic means of weighting the importance of the various performance attributes such that they can be compared on an "apples-to-apples" basis.

The tool used for this task is known as the Technique for Order Preference by Similarity to Ideal Solution, or TOPSIS. This decision-making tool works by ranking the various baseline systems in terms of their fulfillment of the goals and constraints. Different scenarios are addressed by subjectively weighting key system attributes. The results are normalized against a datum (or "perfect design") and a score can then be calculated for each baseline system, per scenario.

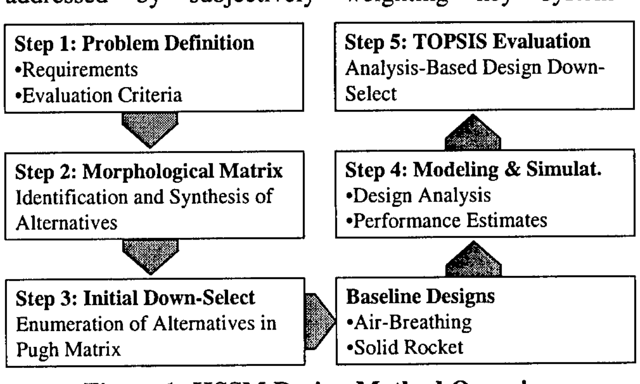

Figure 1: HSSM Design Method Overview

The approach used in this study was to synthesize a set of eight alternative concepts from the morphological matrix, all of which were placed in a Pugh matrix. Next, these alternatives were evaluated on a *qualitative* basis, and from there down-selected to a single solid rocket and a single air-breathing design for detailed analysis. These two designs were then evaluated side-by-side using modeling and simulation in conjunction with TOPSIS to arrive at a final design recommendation for which a detailed technology development plan can be formulated.

Step 1: Definition of HSSM Requirements

The assumed HSSM design requirements used in this paper are based on a set of notional requirements formulated by the American Institute of Aeronautics and Astronautics Missile Systems Technical Committee (MSTC) calling for a weapon with the ability to respond to time-critical targets. This notional request for proposals (RFP) dated 8/3/98 calls for the design of an HSSM weapon that shall be capable of launch from an F-18C, and travel to its target at hypersonic velocities. It is designed to operate in the year 2010, and thus embody technologies producible and operable by this time. The primary targets of this weapon include, but are not limited to: 1) mobile ballistic missile launchers (TCT), 2) surface-to-air missile launchers (TCT), 3) command, control, communications sites, 4) storage, supply depots for weapons of mass destruction, 5) other targets of

Table 1: HSSM Metrics and Constraints

Attribute	*Metric*	*RFP*
Perf.	Peak Flight Mach	>5
(min. time)	Flight Time, sec.	<600[a]
	Range, nmi	>500[b]
Lethality	Warhead Weight, lbs	>150
(brd. Tgt.)	Impact Velocity, fps	>4,000
	Penetration Depth, ft.	>20[c]
	Off-Boresight, deg.	>20
Lethality	Surface Kill Radius, ft.	>150
(sfc. Tgt.)	Off-Boresight, deg.	>20
Cost	ACQ Cost, $1000's	<300[d]
F-18	Launch Weight, lbs	<1,500[e]
Integration	Length, in	<168
	Span, in	<24
Other	No Ejectables	
	Wooden Round[f]	

a: Against Time-Critical Target Only
b: Against Non-Time-Critical Target
c: Reinforced Concrete Target
d: Production Qty 4,000 Units Over 10 yrs; 2010 Entry into Service
e: F-18C Deployable; Must Carry at Least 2 Missiles and Bring Back Aboard Carrier
f: Ready for Loading & Firing Directly from Shipping Container

strategic value.

Table 1 summarizes the key HSSM metrics and constraints, based on the RFP. Note that the combination of flight speed, range, maximum allowable launch weight, and design cost required in the HSSM RFP together represent a considerable advance over today's state-of-the-art capabilities. It is evident that considerable design innovation and technology infusion will be required to achieve these goals in a single design.

Step 2: Morphological Matrix

The morphological matrix is simply a table used to functionally decompose a system. For the HSSM, this means describing the missile system in terms of key subsystems. Therefore, the morphological matrix is used as a brainstorming tool to list all possible ways in which each missile subsystem can be configured. The key to creating this matrix is to select a set of attributes that is broad enough not to exclude significant configurational possibilities, yet specific enough to focus design effort along a few well-defined directions. The morphological matrix for the HSSM design is provided in Table 2.

The next step was to develop a set of eight alternative configurations based on the possibilities enumerated in the morphological matrix. These alternatives were generated by selecting a single vector of design attributes from the matrix, one selection per row. For example, Table 2 has a set of options (vector of attributes) *circled*, one selection per row. This vector of options constitutes one of the eight alternative concepts

Table 2: HSSM Morphological Matrix with Two Design Alternatives Shown: Solid Rocket Concept (Circled), and Ramjet Concept (Shaded)

Characteristics		1	2	3	4	5	6
System	*Cross-Section*	cylindrical	oval	diamond shape	ALCM-like "flattened triangle"	waverider	
	Trajectory	pure ballistic	pure lifting	pulsed propulsion	combination ballistic/lifting		
	Maximum Mach	5.0	5.5	6.0	ballistic maximum		
	Cruise Mach	4.0	4.5	5.0	5.5	6.0	none
Aero	*Lifting Surface*	no wing	fixed wing	variable geometry wing			
	Nose shape	sharp point	blunt, round	blunt, sharp	inlet at nose	nose extension (off-nose shock)	
	Control Effector	none (spin-stabilized)	fins (tail)	fins (canard)	thrust vector control		
Propulsion	*Type*	solid rocket	ram rocket	ATR	ramjet	scramjet	turbojet
	Inlet Type	none	scoop	axisymmetric			
	Fuel Type	pure solid	hybrid solid	gel fuels	standard hydrocarbons	endothermic hydrocarbons	
	External Boost	yes	no				
Structures &Thermal	*Structural Concept*	monocoque	rings, frames, stringers	molded			
	Thermal Concept	hot structure	TPS on internal (cold structure)	combination hot/cold			
	Nose Material	Carbon/Carbon	Ceramic Matrix Composite	Titanium	Inconel	Titanium-Aluminide	hybrid
	Body Material	Carbon/Carbon	Ceramic Matrix Composite	Titanium	Inconel	Titanium-Aluminide	hybrid
	Structural Cooling	ablative	thermal barrier coating	active cooling (fuel)	active cooling (inert chemical)	passive	
	Wing Support	none	fixed	folding			
Electronics/ Avionics	*Guidance*	GPS	INS	combination GPS/INS	astral INS	radar reference navigation	
	Primary Target Acquisition	GPS	radar	optical imaging	lidar		
	Backup Target Acquisition	none	GPS	radar	optical imaging	ladar	home-on laser
	Communications	continuous update	update from F-18 before launch	update on ground before loading	single midcourse update		
	Electronics Cooling	none (therm. Robust systems)	prestored coolant	fuel cooling	heavy insulation		

initially investigated for the HSSM design. The morphological matrix also has a set of options that are *shaded.* This set also forms one of the alternative configurations studied for the HSSM design proposal. These eight alternatives were then compared side-by-side in a Pugh matrix (not shown in the interest of brevity).

Steps 3&4: Initial Down-Select/Modeling & Simulation

Once a population of alternatives is synthesized, the next step is to select a recommended design configuration. Ideally, this is done through rigorous modeling and simulation of each design concept. However, the time and effort required to do a detailed evaluation of the previously defined eight alternative concepts is far greater than the resources available for the task. Therefore, the approach used for the initial down-select is to do a low-level "back of the envelope" analysis for each of the eight alternatives in the Pugh matrix and select two designs for further development.

As there is insufficient space to discuss all eight alternatives, it must suffice to say that the two configurations were selected based on their apparent ability to meet RFP requirements. Subsequently, the best elements of the losing configurations were incorporated into the winning baselines wherever possible. The two designs ultimately selected are the concepts circled and shaded in the morphological matrix. These concepts consist of a solid-rocket powered ballistic missile and a ramjet-powered air-breathing missile, both of which are discussed in detail in reference 5. The next two sections will describe the baseline configurations in detail as well as the performance results estimated via the modeling and simulation tools previously described.

Solid Rocket Baseline

The solid rocket-powered baseline design concept proposed to meet the design requirements previously discussed is a conventional axisymmetric design with a very high propellant mass fraction, and was assigned the designation DKM119-7R. The missile is designed to fly in a ballistic trajectory at very high speed, and features a semi-staged design to enable achievement of high impact velocities necessary to achieve adequate penetration capability against hardened targets. It is designed to be simple and cheap to manufacture, and employs a simple 2-channel control system with a GPS-based guidance system using commercial off-the-shelf (COTS) systems.

Design drawings for the DKM119-7R are shown in Figure 2. The middle drawing shows a planform view of the design, and a notable feature is the large motor size relative to the warhead and guidance package. The 500 nmi range requirement demands an extremely high propellant mass fraction, and this is reflected in the design. Also notable is the large bulge roughly a third of the length of the missile. This bulge separates the motor from the terminal flight package (warhead and guidance modules).

The drawing on the bottom shows an inboard profile for the DKM119-7R. The total missile length is 166 inches, and weighs 1,500 lb. Maximum span is 20.5 inches, with a terminal flight package maximum diameter of 10 inches. Notable features include the integral gas bottles (2), staging mechanism, control surface arrangement, internal configuration, and nozzle/case design. The integral gas bottles store high pressure nitrogen used to power the control surfaces in flight, and are located in the guidance section as well as the nozzle throat region. Integral gas bottles allow reduced structural mass because the pressure bulkheads are redundant with the existing structural shell of the missile. In addition, the storage volume can easily be tailored to capitalize on existing space, and bottle manufacture is simple, consisting of a single-pass weld. Bottle positioning around the nozzle throat area has added benefits of 1) pre-stressing the nozzle to help ensure throat area design intent using less structural material, 2) cooling of nozzle structural shell via heat transfer into bottle gas, 3) energization of bottle gas via heat transfer, allowing use of a smaller bottle for same control energy.

Design details of the staging mechanism are of interest because this is a key to the viability of the DKM119-7R design concept. *The staging mechanism incorporates the unique feature of allowing the terminal flight package to be a flight-line changeable item, which facilitates quick turn-around times, simplifies flight line logistics, and enables the concept of a derivative product family to be realized.* The central idea is that if a series of terminal flight packages can be built on a single motor design, then the same motor can be used for a variety of purposes. One need only change the terminal flight package to adapt the weapon for a particular purpose. This allows quick adaptation of the basic design to current needs, both at the flight line level and at the product design level, as described in detail later on. It is assumed that the launch lugs are attached to the motor case via a strong back that allows the launch lug position to be moved to match the missile CG position as the weight of the terminal flight package varies.

The control surface arrangement consists of a set of four jet vanes located in the nozzle diverging section and a set of four slab-surface movable control fins in the nose section. The jet vanes are used for control during the initial phases of flight when the motor is in operation, and are manufactured of carbon-carbon composite material. The four tail fins are fixed and are used to augment stability. The four front fins are not in operation during the initial flight, but are put into operation at the start of reentry, and operate for the remainder of the flight. All controls are powered by compressed nitrogen.

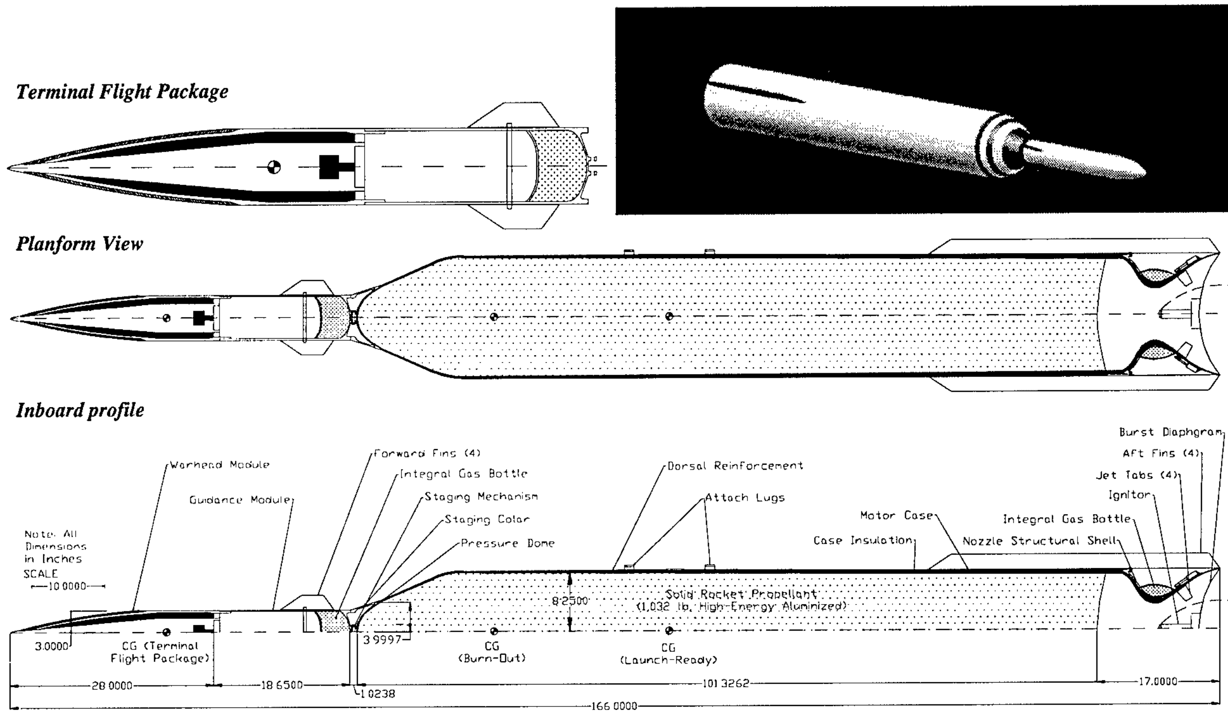

Figure 2: DKM119-7R Configuration, Inboard Profile, and Major Design Details.

The internal arrangement is designed for maximum volumetric efficiency within the envelope restrictions allowable for aircraft compatibility. The warhead was intentionally placed in front of the guidance package to help shield the guidance computers from the extreme thermal loads imposed by the high flight Mach numbers. In addition, location of the warhead in the nose increases packaging efficiency. In order to have adequate volume for motor propellant, the outer case mold line diameter is 16.5 inches. However, the high impact velocity demands a terminal flight package with a high ballistic coefficient, and thus, the terminal package diameter is much smaller than the motor, giving the missile the distinctive shape of a high power rifle cartridge.

Finally, the nozzle design is a high performance, high area ratio configuration of single piece, rolled shell manufacture. The nozzle bolts onto the rear of the motor case shell for simplicity of manufacture and assembly. The case has a constant outer-diameter, with a mild hip at the front. The terminal flight package is connected to the case via a single bolt at the nose of the case, and a mating collar that transfers flight loads from the eight-inch diameter load platform on the case shell to the six-inch diameter terminal flight package. It was elected to use an eight-inch diameter load-bearing platform because it allows heavier nose packages to be attached in the future, whereas, if a six-inch platform were used, there would be a severe limitation of growth potential. Thus, a heavier configuration with a mating collar was selected in spite of the weight, complexity, and cost penalties in the interest of product growth capability.

The top two drawings of Figure 2 show the terminal flight package detail and an isometric view of the missile. Note that the terminal flight package is very small relative to the motor, and is very simple in design. The guidance system is COTS using GPS navigation with an INS backup. The major assemblies consist of a warhead module, a guidance module, a motor case module, and a nozzle module. The simple design and modular nature of these assemblies greatly facilitates their separate manufacture at remote sites and later assembly in a single area. In fact, the terminal flight package and the motor module need not (and in fact should not) be assembled until it is placed on the aircraft wing. The bulk of the electronics are located in the guidance section with only minimal electronics content in the nozzle section and warhead fusing. The warhead itself is a multi-mode device capable of being used in either a blast/fragmentation or herd-target penetration mode. All structural pieces requiring highly specialized manufacture are located in the nozzle and case, with the guidance section structure consisting of a simple tube with end cap and an internally-welded bulkhead, and the warhead case consisting of a precision casting.

Use of a conventional axisymmetric design allows a greatly reduced production cost, facilitates missile modularity, and simplifies design and manufacture. *However, the most important feature of the modular axisymmetric design is that it facilitates the development of a "derivative family" concept of manufacture. This concept has the potential to drastically reduce unit cost by amortizing development, tooling, and production costs over much larger production runs than is possible using*

a conventional product development approach. This derivative family concept is key to achievement of the aggressive cost goals set forth in the RFP.

Derivative Missile Family Concept

The fundamental basis of the cost-control strategy employed in this design is the realization that the best way to drastically reduce unit cost to the levels targeted in this proposal is to lengthen production runs and fit the production rate to match the capacity of the available manufacturing capability. The key to making this happen is *product standardization and development of a family of derivative products based on a common design.* This concept, above all others, will enable achievement of unit cost targets proposed here.

The concept proposed here is to use the basic rocket motor module as a building block for a family of products. This idea is illustrated in Figure 3, which shows a hypothetical family of missiles all based on the same motor. For instance, it is possible to mount a 350 lb warhead package on the 8 inch load pad of the rocket motor to create a medium-range standoff missile. Attachment of an air-to-air package would create a long-range air-to-air missile in the AIM-120 Phoenix range class. It may even be possible to develop more exotic weapons, such as a two-stage anti satellite weapon that uses the high-performance solid rocket motor of the DKM119-7R as the first stage.

Such an arrangement has the ability to drastically reduce the unit cost of the motor because the production run would be much larger than that of the DKM119-7R alone. Using such a concept, it would be possible to procure a lot of motors as a separate buy from the payload package, which *increases procurement flexibility.* It would be possible to ship bare rocket motor modules to the site of a regional conflict, and then use these modules with whatever warhead need be used at the time, thus *increasing logistical flexibility.* It would be possible to easily upgrade existing hardware in the field, *increasing technology transition flexibility.* It would even be possible to park aircraft on the ramp with bare rocket motor modules on the pylons, attaching the payload modules according to the instantaneous mission needs, be it medium range standoff attack, anti-ballistic missile combat air patrol, or long-range attack of point targets, thus *increasing operational flexibility.* Finally, such a concept would enable companies to rapidly respond to defense requirements by leveraging existing hardware designs towards new payload modules based on the same motor module, thus *increasing product line flexibility.*

An obvious extension of this concept would be development of motor modules, each of a specific total impulse class. The DKM119-7R motor module would serve as the foundation for the large-impulse class of missile motor, with other motor designs focused on the

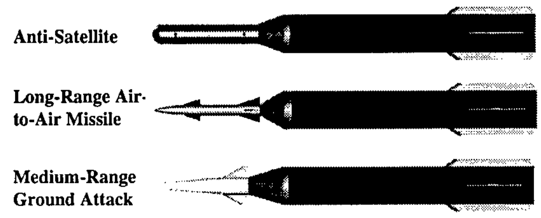

Figure 3: Derivative Missile Concepts Based on DKM119-7R Rocket Motor Module

medium and low impulse classes, rounding out the propulsion spectrum. Moreover, if the staging/payload attach mechanism were standardized across all missiles, various sized motors could be used for the same payload package. For instance, a single air-to-air package would be used with large impulse motors to make a long-range missile, and short-range motors to make a short-range AAM. Finally, it would be possible in this environment to separately bid motor and payload. As a result, motors would become a commodity, with different manufacturers competing for various motor contracts.

It is believed that this concept, more than any other, has the potential to make the cost goals defined for this missile obtainable. If such a concept can be implemented on a wide scale, the economies of scale achieved through standardized production of missiles as a commodity should be nothing less than revolutionary.

Design Drivers and Trade Philosophy

As mentioned previously, the principal driver for this design is low unit cost. *When making design decisions involving trades on cost, all requirements were considered to be negotiable in the interest of reduced unit cost.* Since weight is closely related to cost, the design weight constraint of 1,500 lb was considered to be firm, and some compromises in design performance were accepted in the interest of reduced weight (and cost). This is the basic philosophy guiding the design decisions for the DKM119-7R concept.

The main system-level design drivers for this concept are given in Table 3. The $300K unit cost is the

Table 3: Design Drivers on DKM119-7R Configuration

Design Drivers	*Consequence*
500 Nmi Range	• High Propellant Weight Fraction • High Specific Impulse Motor • Complex Case And Nozzle Structure • Extremely High Energy Propellant
$300k Unit Cost	• Modular, Product-Family Design • COTS Guidance System • Simple Axisymmetric Construction
4000 Ft/S Terminal Velocity	• Extremely High Ballistic Coefficient • High Fineness Ratio • Ejectable Motor Case
TCT Reaction Time <10 Min	• High Flight Speeds → Ballistic Flight

primary motivation for the introduction of a product family-oriented configuration. It also drives the use of commercially available guidance hardware, as well as the selection of a simple axisymmetric configuration. The range requirement demands an extremely high propellant weight fraction as well as a high specific impulse for best performance. This in turn drives the rocket motor design to use a complex case and nozzle structure to achieve light weight with high performance. Finally, the range requirement implies that the propellant must have an extremely high energy density in order to maximize motor impulse.

Another strong driver on the missile configuration is the 4,000 ft/s terminal velocity requirement needed to achieve adequate penetration against hardened targets. This implies that the terminal flight package must go into a powered dive and/or have an extremely high ballistic coefficient. It was elected to design a terminal flight package with an extremely high ballistic coefficient rather than have a two-stage, powered-dive configuration because the added cost, weight, and complexity of having an extra motor, nozzle, igniter, etc. was deemed to be insufficient relative to the performance benefit. However, one must still have a staging mechanism so that the empty motor case can be discarded after use. The terminal velocity requirement also drove the small (six inch) radius and high fineness ratio of the terminal flight package.

Finally, the reaction time of 10 minutes against time critical targets implies very high flight speeds. The drag associated with flight at this speed in the sensible atmosphere (below 120,000 ft) is high enough that one must use sustained propulsion throughout the flight. In order to get sustained propulsion from a solid rocket motor for 10 minutes, the thrust would be too low to maintain powered flight. Therefore, the only option is to use a ballistic flight path in which takes the missile out of the sensible atmosphere for part of its flight. Thus, the time requirement in conjunction with the range requirement drove the selection of a ballistic flight profile. In addition, the long length of the terminal flight package, in conjunction with the large propellant mass and 168 inch length requirement, drove the motor case diameter to 16.5 inches.

Requirements Compliance Matrix

The requirements compliance matrix for the solid rocket design is shown in Table 4. The order of precedence for design trades is generally taken to be: 1) cost, 2) weight, 3) TCT response time, 4) range, 5) terminal velocity. This general philosophy is reflected in the compliance matrix, as a great deal of focus is given to meeting cost and weight constraints within the envelope restrictions of current launch platforms (F-18C). As such, all basic dimensional envelope requirements are met, as are launch weight limits. As is discussed later, most of the performance objectives were met, but trades

Table 4: DKM119-7R Requirements Compliance

Requirement	*Go/No-Go*
500 Nmi Range	✔
Air Launched, F-18C Compatible	✔
Max. Mach Number > 5	✔
Time to Target for TCTs < 10 Min.	✔
Off Boresight Launch > 20 Deg.	✔
Length < 168 Inches	✔
150 lb Warhead w/ 150 Foot Blast Radius	✔
Concrete Penetration Depth of 20 Feet	✘ (18 ft)
4000 ft/s Impact Velocity	✔
Average Unit Production Cost of $300K	✔
Wooden Round	✔
No Ejectables	✘
1,500 Lb Launch Weight	✔

on performance in the interest of weight and cost were necessary. The ejectables requirement is violated for this design in the interest of reduced cost (derivative family concept) and terminal flight velocity (high terminal package ballistic coefficient).

Air-Breathing Baseline

The DKM119-4A high speed standoff missile is a hypersonic ramjet-powered, long-range, precision-guided weapon developed to meet the design requirements for next-generation quick response to time critical targets at minimal per-shot cost. The missile is designed to use high-precision target coordinates supplied by off-board assets as its principal means of targeting and is guided in flight by a GPS/INS equipped package to fly to and destroy time-critical targets of opportunity. Once GPS target coordinates are available, the weapon is launched from an aircraft at patrol altitude, is boosted to ramjet takeover speed using a solid rocket motor, and then cruises to the target area at Mach 5. Once in the vicinity, the missile is designed to perform a terminal dive onto the target where the multi-mode warhead is detonated in either a blast/fragmentation mode for destruction of surface targets, or in a penetration mode for destruction of hardened targets.

The DKM119-4A is designed to perform at minimal cost and with maximum flexibility. The design features simple and modular construction that simplifies manufacturing, maintenance, and upgrades. The propulsion system contains no moving parts and is designed for high reliability/low cost. It uses an annular fuel tank with a high heat-capacity endothermic fuel to protect the warhead, guidance computers, control system, and fuel control system from the harsh, high-temperature flight environment, all without the need for extensive use of exotic materials technologies.

This avoidance of exotic high-risk technologies is key to delivering a low-cost solution to the requirements within the desired development timeframe. Moreover, COTS components are used wherever possible in the interest of reducing unit cost. For example, the guidance

system is built entirely from off-the-shelf components, and the use of GPS/INS terminal guidance precludes the need to put expensive seeker equipment on-board, further reducing unit costs.

An inboard profile of the basic design is given in Figure 4. Overall length is 168 inches, maximum span is 24 inches, and launch weight is 1,480 lb. Note that the design is axisymmetric with a simple cylindrical body rather than a flattened lifting-body. There are several reasons for this, the most important of which is that it reduces manufacturing costs considerably over custom-molded bodies by simplifying part geometry, fabrication, and assembly. Moreover, the axisymmetric configuration facilitates design flexibility by allowing a simple modular design in which modules can easily be upgraded independent of the surrounding vehicle. Additionally, the axisymmetric configuration is desirable from a surface heating point of view, as it has less wetted area than other configurations, and is structurally efficient because pressure loads are carried in pure hoop stress.

The design features an axisymmetric, fixed-geometry conical inlet mounted on the nose of the vehicle. The axisymmetric inlet is used because it is relatively simple and cheap to manufacture, while delivering acceptable inlet pressure recovery and off-design drag characteristics. The inlet employs no bleed or bypass in the interest of simplicity and cost, and is sized to match ramjet engine flow demand at the design-point cruise fight condition of 89,000 ft and Mach 5.

The DKM119-4A is controlled using movable canard surfaces located just aft of the inlet and mounted on the forward fuselage frame that separates the inlet and main body modules. The main body module consists of an annular fuel tank wrapped around the warhead, guidance module, high pressure gas bottle, and fuel control module. The fuel tank geometry is designed to give maximum thermal protection to sensitive components while being structurally efficient. This fuel tank is the primary load-bearing member connecting the forward section to the ramjet module, and is pressurized during ramjet operation, both for added bending stiffness and to provide high-pressure fuel to the fuel control system.

As mentioned previously, the warhead is a multi-mode design identical to that used in the DKM119-7R, as is the guidance computer hardware used in the guidance module. A high-pressure nitrogen gas bottle is mounted immediately aft of the guidance module and is used for fuel tank pressurization, control system actuation, and internal cavity purge (to ensure hot gasses are not able to enter the core bay area and overheat sensitive components). The fuel control module uses a simple pressure-fed fuel system to feed fuel to four injectors in the ramjet combustor. The use of four injection points in the combustor facilitates efficient combustion and enables reasonably high turn-down ratios by staging the

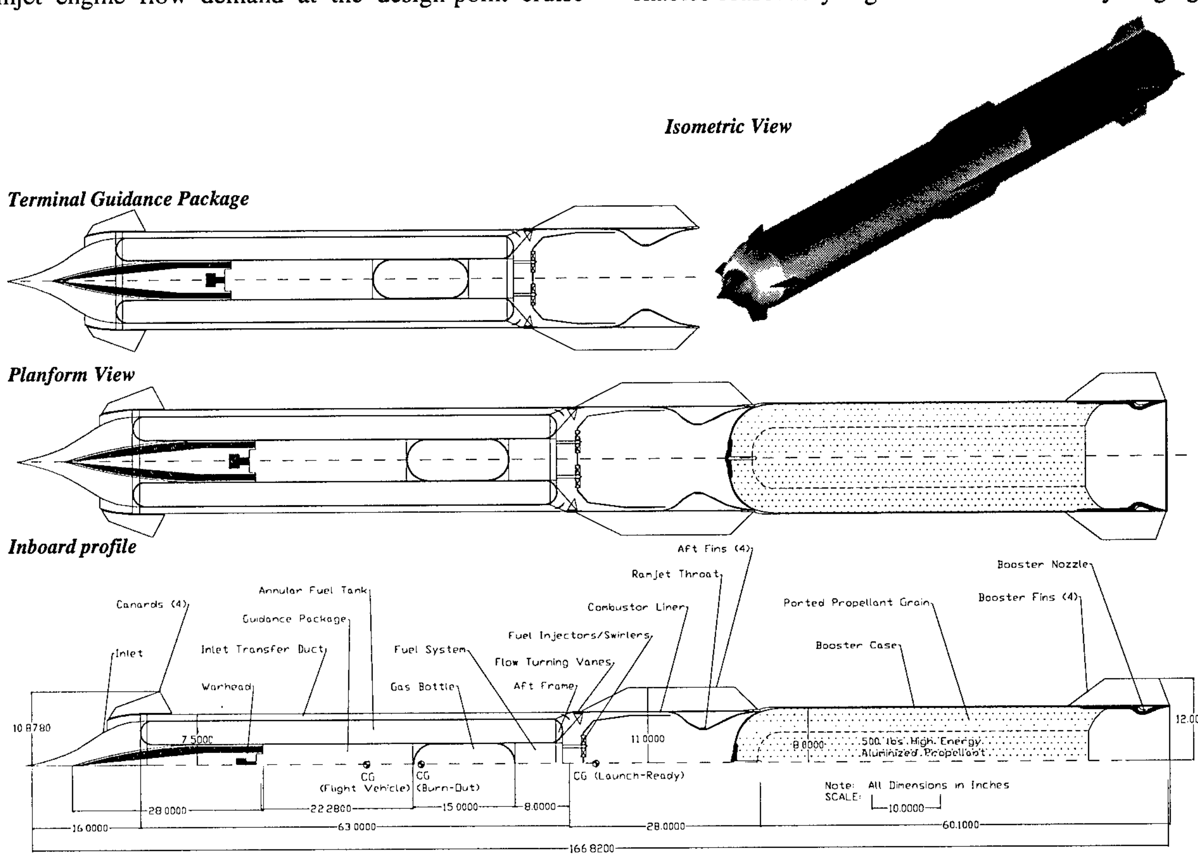

Figure 4:DKM119-4A Configuration, Inboard Profile, and Major Design Details.

burners appropriately.

The ramjet combustor and nozzle are built as a single module that bolts on to the mid-frame separating the ramjet module from the main body package. The ramjet module features a four-cup vortex swirler combustor liner identical to those used in aircraft gas turbine engines today. Although the swirler design is more complicated and expensive than the spray-bar arrangements typically used in ramjet combustors, is allows much higher combustion efficiencies than are possible using spray-bars, and also facilitates swirler staging for part throttle operation.

The ramjet is fed by an axisymmetric transfer duct that moves the inlet air around the main body package and back to the ramjet combustor. Note that the transfer duct discharge features a turning vane and a lobed turning tab to promote the smooth flow of air into the collection reservoir immediately forward of the swirlers. The combustor liner and nozzle are all air-cooled and are constructed of conventional high-temperature alloys. The ramjet module also has a set of fixed fins attached to the exterior which are used for aerodynamic stability as well as stiffening of the load-bearing ramjet module case. The ramjet nozzle exit plane incorporates a structural ring that girths the nozzle and acts as the thrust frame to transfer loads from the booster into the ramjet case.

Finally, the aft 40% of the missile length consists of a solid rocket booster used to propel the missile from launch speed to ramjet takeover speed. This booster contains 500 lb of high-energy propellant and produces 7,000 lb of thrust during the eighteen-second boost phase, burning out at Mach 3.3. After burnout, the booster is designed to fall away and the ramjet takes over. Although it is possible to use a smaller booster and have ramjet takeover at an earlier time, the disadvantage of this is that ramjet specific thrust is very low at these Mach numbers, and results in poor acceleration relative to the solid rocket booster. As this is in direct conflict with the time-to-target requirement, it was opted to use a larger booster since the range requirement could be met with reasonable confidence. A conventional booster was selected due to its low risk/cost, although this design does not comply with the "no ejectables" requirement. One possible solution is to use an integral ramjet/booster and this is a technology worthy of further investigation. Note also that the booster module incorporates a set of aerodynamic fins to ensure static stability during the boost phase when the weight of the booster draws the missile center of gravity aft.

The figure above the inboard profile shows a full axisymmetric view of the DKM119-4A design. Note the high volumetric efficiency of the overall design due to the annular fuel tank arrangement. The CG travel in flight is minimal because the fuel tank CG is nearly coincidental with the vehicle CG, simplifying the control system complexity and reducing development cost. Note the relatively short inlet length and correspondingly low nose fineness ratio. Since the inlet design has no boundary layer bleed on the intake ramp, it is necessary to keep the inlet ramps short to minimize the impact of boundary layer separation on inlet operation.

The manufacturing breakpoints for the DKM119-4A design consist of an inlet, main body module, ramjet combustor with nozzle, and booster module. The main body module is in turn broken into two sub-modules and three assemblies: the warhead and guidance modules, and gas bottle, fuel system, and main fuel tank assemblies. This arrangement allows any major module to be replaced independent of its surrounding modules, thus increasing upgrade flexibility and maintainability. Second, it facilitates ease of manufacture. Finally, and most importantly, *it facilitates subcontracting of the booster and ramjet module design and manufacturing to those companies whose core competency is in these areas.* This "core competency" production concept is based upon the idea that the best way to reduce product costs is not to produce the entire missile "in house," but rather to subcontract key components to those companies whose core competency is in those fields. This concept is key to reducing DKM119-4A unit cost and overall design risk.

Design Drivers & Trade Philosophy

The highest-priority design driver on the configuration of the DKM119-4A missile is unit production cost. This requirement has received the preponderance of attention because it will be difficult to meet using air-breathing missile designs due to their inherent complexity. Thus, considerable effort will be devoted towards strategies to reduce cost, and this section will show that the cost goals have a pervasive impact on the overall design. In addition, this section will explain what are the other important design drivers and how they impact the design of the missile.

Other important design drivers on the DKM119-4A besides cost are weight (which is usually closely associated with cost), and performance. When design trades are necessary, the order of priorities used for the DKM119-4A is: cost, weight, time to target, range/ payload, all others. This priority ranking can be explained as follows: cost must be first because it is a high customer priority and failure to meet this target will greatly increase the program's vulnerability to cancellation. Weight is important because it is closely related to cost and because the launch weight (and geometric dimensions) must stay within the standard missile envelope common to most aircraft in order for the missile to be widely compatible with existing equipment (thus increasing sales potential). The fundamental purpose of the DKM119-4A is to fill a void in operational capability, namely quick response to time-critical targets. Thus, the time to target requirement must be met, otherwise there is little justification for building the

missile in the first place. Range and payload are always important to any missile system, and it is seldom possible to get more than enough of either. Finally, meeting all other requirements is important also, and every effort has been made to ensure that the DKM119-4A satisfies all of these. However, satisfaction of these requirements will not come at the expense of the previous four.

The primary design drivers on the configuration of the DKM119-4A are summarized in Table 6. Note that the cost requirement drives many aspects of missile design, as previously mentioned. In addition to the weight, time, and range loads, the fact that the missile must fly at Mach 5+ in the atmosphere implies that the thermal loads on the airframe will be severe. This has a strong impact on the internal configuration of the missile, as well as on the material selection for airframe structures.

Requirements Compliance Matrix

Design compliance of the DKM119, model 4A with RFP requirements for high-speed standoff missiles is summarized in Table 5. The requirements emphasis is on meeting range and time-to-target goals while driving down the unit-cost as much as possible. Note that the design meets all requirements except three, those being unit cost, no-ejectables, and penetration depth requirements. The first is due to the inherent complexity of an air-breathing design, while the second is due to the boost requirements to reach ramjet takeover speed.

The DKM119-4A meets the 500 nmi range requirement, and could be optimized to go considerably farther. The design is compatible with the F-18C in terms of hardware, dimensional envelope, and launch envelope. The maximum Mach number is greater than 5 and the missile has 180° off-boresight launch capability. The design cost is $495K, 66% above target and impact speed, penetration depth, and ejectable requirements are not met, though it is likely the last three could be met with the addition of an integral booster ramjet design. Finally, the design meets the launch weight limit with a 20 lb weight margin.

Concept Evaluation and Selection

Up to this point, the performance of the two candidate designs has been presented in great detail, and each was revealed to have some inherent strengths and weaknesses. However, the process of down-selecting to a single design requires consideration of a variety of attributes and performance parameters, most of which cannot be compared on an "apples-to-apples" basis. Therefore, it is simply not possible to make this decision based on classical optimization techniques. Instead, the final decision rests largely upon intuitive judgement on the part of the evaluator.

This intuitive approach to systems design has yielded highly successful systems in the past, and may yet continue to do so in the future. However, there are several factors that are making it increasingly difficult to rely solely on an individual's intuitive judgement. First, acumen in judgement comes from experience in making many similar judgements. However, there are fewer systems in development today, and consequently, there are also fewer opportunities for decision-makers to hone their skill. Second, the cost of modern aerospace systems is continuing to spiral ever upward. Consequently, the financial stakes of design decisions are increasingly grave with each successive generation, and shareholders are naturally reluctant to rely solely upon the judgement of a single individual when the decisions could "make or break" the company. Finally, the complexity of modern aerospace systems is growing considerably over the previous systems. Therefore, it is increasingly difficult for any single person to become a true "expert" in every discipline necessary to evaluate a design.

The upshot of this situation is that there is a strong

Table 6: Primary Design Drivers on DKM119-4A Configuration

Design Drivers	*Consequence*
$300K Unit Cost	• Modular Design • COTS Components • Simple Geometry (Axisymmetric) • Strap-on Booster • "Core Competence" Business Strategy
Weight < 1,500 lb	• Axisymmetric Cross-section • Simple and Efficient Load-Bearing Structure • 3 Simple Fuselage Frames • Simple Pressure Shells
Time to Target < 10 min	• Large Booster for Quick Acceleration • M5+ Cruise Speed → Large Aero-Heating Loads • Canard-Mounted Controls (Due to Large Booster)
Range > 500 nmi	• Low Ramjet SFC → Conical Inlet+Vortex Swirlers • Low Empty Weight, Small Warhead Size
Aero-Heating Loads	• Temperature-Tolerant "Superalloy" Case Materials • Annular Fuel Tank w/ Endothermic Fuel • Low Wetted Area → Axisymmetric Cross-section • Gas-Operated Controls
Impact Velocity	• Dynamic Pressure-Tolerant Airframe to 200 psia • Powered Flight into Target → Reduced Range

Table 5: DKM119-4A Requirements Compliance

Requirement	Go/No-Go
500 Nmi Range	✔
Air Launched F-18C Compatible	✔
Max. Mach Number > 5	✔
Time to Target for TCTs < 10 Min.	✔
Off Boresight Launch > 20 Deg.	✔
Length < 168 Inches	✔
150 lb Warhead with 150 Foot Blast Radius	✔
Concrete Penetration Depth of 20 Feet	✘
4000 ft/s Impact Velocity	✘
Average Unit Production Cost of $300K	✘
Wooden Round	✔
No Ejectables	✘
1,500 lb Launch Weight	✔

impetus to develop formalized methods and tools to assist the designer in the multi-attribute decision-making process. This section will describe a formalized selection methodology that can be used to down-select to a single design. This method will then be applied to assist in the design down-select for the HSSM design concept of choice for this paper.

Baseline Performance Results

The performance results for the solid rocket and air-breathing baseline HSSM designs are summarized and compared against the RFP requirements in Table 7. Note that the HSSM design requirements are grouped into 4 broad categories: performance, lethality against a buried target, lethality against a surface target, and cost. The F-18 compatibility constraints and 1,500 lb weight limit are *not* included in this matrix because they were taken as "design to" constraints for both concepts. Consequently, it is assumed that both concepts are completely equal in terms of compatibility and launch weight, which means that neither of these requirements impact the selection process. Also, the no-ejectables requirement was violated for both concepts, so it also has no significant impact on the selection process and is therefore not included in the evaluation matrix. It is clear from Table 7 that the DKM119-7R has significant performance and cost advantages over the "-4A" configuration.

Step 5: Design Down-Select via TOPSIS

The next step is to evaluate these two designs and down-select to a single design recommendation. The tool used to assist in this decision is TOPSIS,[6] or Technique for Order Preference by Similarity to Ideal Solution. TOPSIS is a systematic means for ordering the various alternative systems studied in terms of their fulfillment of the metrics and constraints. It works by estimating a total product score based on the various performance metrics, where the influence of each requirement is normalized based on a weight assigned to each performance attribute to reflect the importance of that requirement. Different scenarios (such as hard target or soft target scenarios) are addressed by subjectively weighting key system attributes according to the needs of each scenario.

The first step is to normalize the results of Table 8 against a datum and score results for each alternative system, per scenario. For the HSSM, the datum was taken as a fictitious missile whose metrics lie directly on the specified constraints (system requirements). For example, the datum missile has a maximum Mach number of 5, a range of 500 nmi, and an impact velocity of 4000 ft/s. Thus, a design that exceeds the requirement in a particular category will have a score higher than 100%, while a design that falls short will score less than 100.

The next step is to select weighting factors for each attribute of significance. The weighting factors selected for this study are shown in Table 8. Since different evaluators generally have unique estimates of how the importance weighting should be distributed amongst the four merit categories considered, several likely weighting scenarios are given. Two broad categories of scenario are considered, these being wartime use and "police action" use, the primary difference being that the latter class of application is assumed to be more cost-sensitive than all-out wartime application. These two classes of conflict are further subdivided into two target types, these being non-time-critical and time-critical targets (the latter is assumed to be more sensitive to performance than is the former). Finally, these four classes are further divided into surface (soft) targets and buried (hardened) targets. Thus, a total of eight weighting scenarios are considered.

Table 7: HSSM Performance vis à vis Requirements

Attribute	*Metric*	*Solid Rocket*	*RFP*	*Air-Breather*
Perf.	Peak Flight Mach	8.7	5.0	5.0
(min. time)	Flight Time, sec.	456.0	600	768.0
	Range, nmi	497.6	500	500.0
Lethality	Impact Velocity, fps	4,385.0	4000	<2,500
(brd. Tgt.)	Penetration Depth, ft.	17.8	20.0	~10.0
	Off-Boresight, deg.	180	180	180
Lethality	Surface Kill Radius, ft.	150	150	150
(sfc. Tgt.)	Off-Boresight, deg.	180	180	180
Cost	ACQ Cost, $1000's	285.9	300	495.4

The equation used to generate the system scores, per scenario, is given by

$$\text{Score} = \sum_{i=1}^{4}\left(WF_i \times \prod_{j=1}^{n_i} \frac{M_j}{M_j\big|_{datum}} \right) \quad (1)$$

The **i** values in Equation 1 correspond to the four

Table 8: HSSM Effectiveness Results for Various Weighting Scenarios

Wartime Use

	TCT		non-TCT	
Attribute	Surface	Buried	Surface	Buried
Performance	60%	60%	50%	50%
Lethality: Surface	25%	0%	35%	0%
Lethality: Buried	0%	25%	0%	35%
Cost	15%	15%	15%	15%
DKM-119-7R	140.0%	152.8%	126.2%	144.1%
DKM-119-4A	55.96%	80.96%	48.15%	83.15%

Police Action Use

	TCT		non-TCT	
Attribute	Surface	Buried	Surface	Buried
Performance	30%	30%	20%	20%
Lethality: Surface	30%	0%	40%	0%
Lethality: Buried	0%	30%	0%	40%
Cost	40%	40%	40%	40%
DKM-119-7R	112.6%	128.0%	98.8%	119.3%
DKM-119-4A	47.66%	77.66%	39.85%	79.85%

attributes (performance, lethalities, cost). **WF** denotes the weighting factor for the $\mathbf{i}^{th}$ attribute. **j** is the number of metrics comprising the $\mathbf{i}^{th}$ attribute. The **M** values are the values of each of the **j** metrics, and "datum" refers to the value of $\mathbf{M_j}$ for the datum missile. The fraction term in the above equation indicates a "higher-the-better" metric, i.e., a metric for which the highest value is desirable. For "lower-the-better" metrics (time of flight and cost), the reciprocal of the indicated fraction is used.

The results from TOPSIS analysis of the eight weighting scenarios are shown at the bottom of Table 8. It is evident from the scores that *the DKM-7R emerges as the clear victor for all eight scenarios due to its superior time-to-target, penetration, and cost performance.* In fact, with the exception of the ejectables requirement, it met or surpassed all RFP requirements except penetration depth. It should be noted here, however, that the DKM119-4A concept could be considerably refined to improve its performance, particularly with respect to its range performance. Therefore, if range performance were a stronger driver in the HSSM design, the air-breathing design would be the weapon of choice over the solid rocket, particularly because it has greater potential for range and payload growth than the solid rocket.

Conclusions

The primary objective of this paper was to demonstrate how several methods from decision theory can be applied to the missile design process. Specifically, it was shown that the morphological and Pugh matrices are useful tools for assisting the designer in organizing and synthesizing design alternatives in the face of almost limitless options. It was also shown that TOPSIS can be used to assist in the multi-attribute decision-making process apropos a design down-select.

In addition to demonstrating new methods, the results of this study suggest that it is possible to construct a relatively low-risk solid rocket-powered missile capable of simultaneously achieving the range, speed, weight, and cost targets defined in the 1998 MSTC RFP. In fact, *it appears that solid rocket-powered configurations are in many ways superior to the air-breathing designs and warrant further investigation and development as viable design concepts for meeting the HSSM requirements.* This is not to say that air-breathing concepts can be rejected out-of-hand based on the results presented here. The scope and depth of the air-breathing concept analysis is simply too limited to permit a sweeping conclusion. Nevertheless, the solid rocket-powered concept appears to be a strong contender worth more consideration than it has heretofore received for the HSSM application.

It is further suggested that a key strategy towards driving cost down is to adopt a product family approach similar to the "core engine" philosophy used in the aircraft engine business wherein a single (expensive-to-develop) engine core us leveraged for a variety of applications. A similar strategy could be used for a HSSM missile wherein a common propulsion unit could serve as a platform for a variety of products, thereby increasing commonality, reducing development costs for derivative systems, and amortizing tooling and production costs over much larger production runs.

Finally, several innovative design features were suggested for incorporation into HSSM designs. These include the use of an integral gas bottle in the solid rocket configuration to save weight and cost, the use of a flight-line changeable terminal flight package, and the use of an oversized staging collar for future payload growth. In addition, both designs feature a highly modular arrangement (contrary to fashionable lifting-body designs) that facilitates easy assembly, work-share splits, and product derivatives/upgrades.

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PART I

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